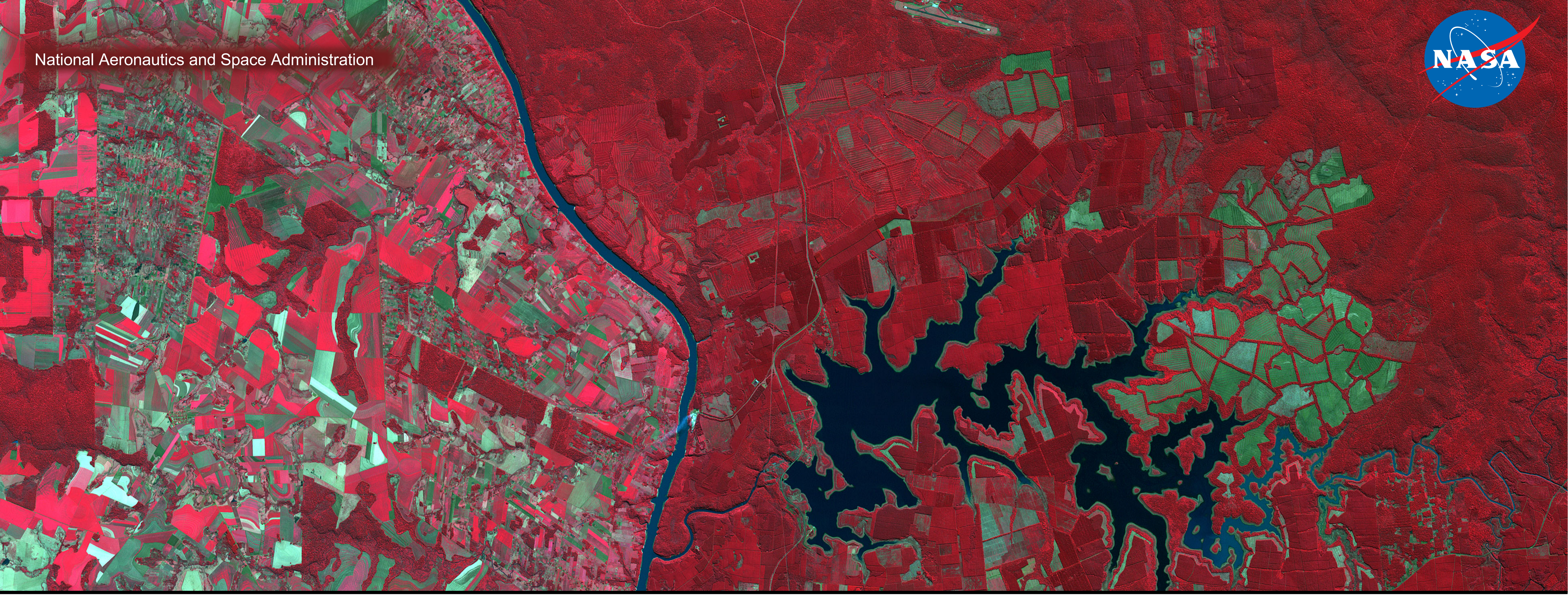


Overview of Evapotranspiration

Amita Mehta, Ana Prados, Erika Podest

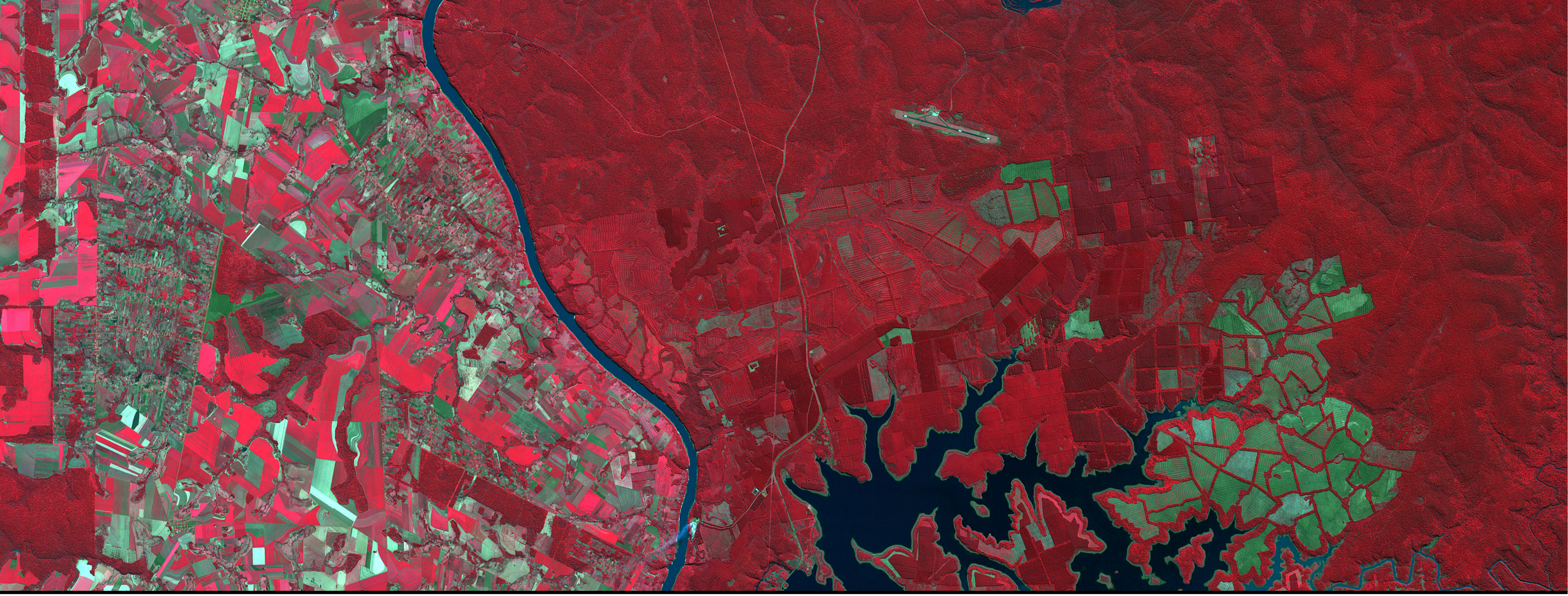
1 December 2017

Learning Objectives

- Understand methods of estimating evapotranspiration (ET) using remote sensing
  - Identify NASA satellites and sensors used for ET estimation
  - Access ET data

Presentation Outline

- Importance and Challenges of ET Estimation
- Methods of Estimating ET Based on Remote Sensing
- Overview of ET Data Products
- Applications of ET data
- METRIC: Mapping Evapotranspiration at high-Resolution with Internalized Calibration



Importance and Challenges of ET Estimation

What is Evapotranspiration (ET)?

- The sum of evaporation from the land surface, plus transpiration from plants
- ET transfers water from the surface to the atmosphere in vapor form
- Energy is required for ET to take place (for changing liquid water into vapor)

Importance of ET

- Critical component of the water and energy balance of climate-soil-vegetation interactions
- Useful for:
  - determining agricultural water consumption
  - assessing drought conditions
  - developing water budgets
  - monitoring aquifer depletion
  - monitoring crops and carbon budgets

Challenges in Measuring ET

- ET depends on many variables:
  - solar radiation at the surface
  - land and air temperatures
  - humidity
  - surface winds
  - soil conditions
  - vegetation cover and types
- Highly variable in space and time

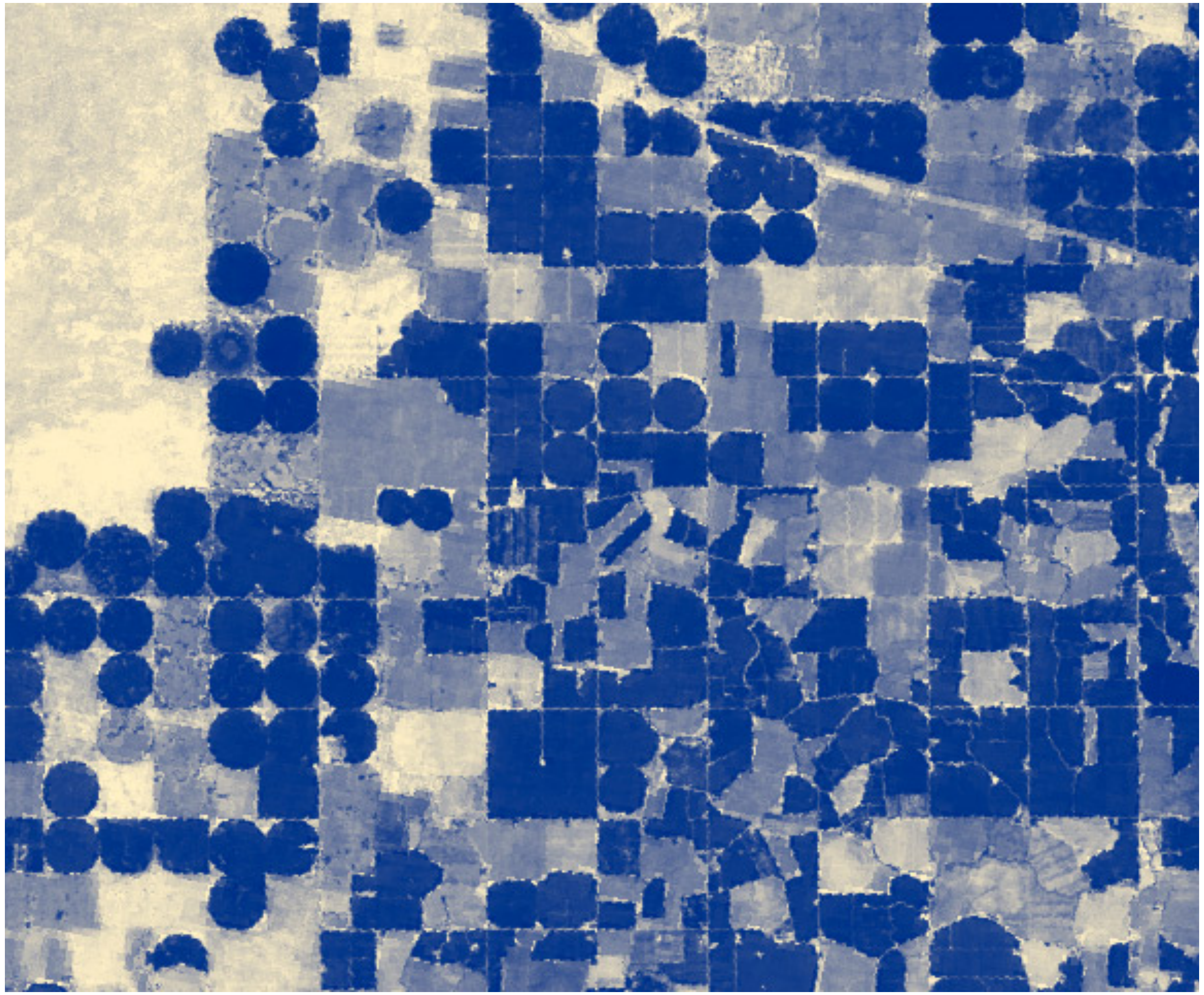


Image Credit: NASA Earth Observatory, Robert Simmon, based on data from the Idaho Department of Water Resources

ET Ground Measurements

- Limitation
  - Point measurements and cannot capture spatial variability

Eddy Covariance System

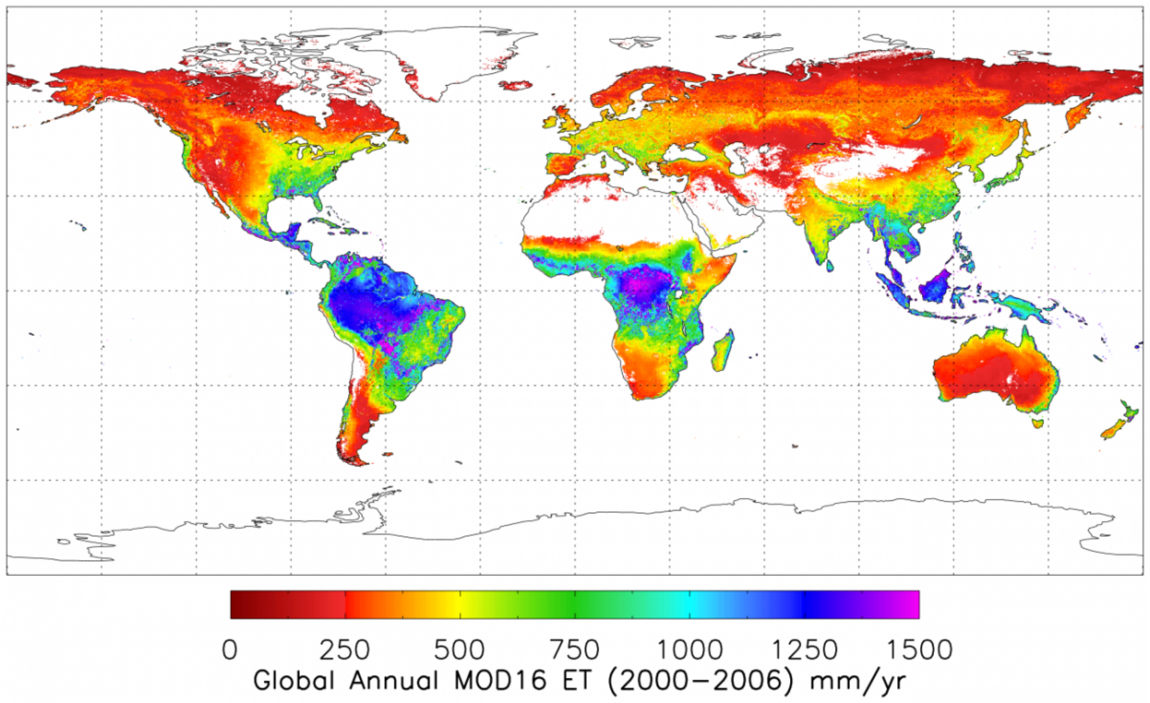
Lysimeters

Image Credit: (left) AmeriFlux, Dept of Energy; (right) USGS

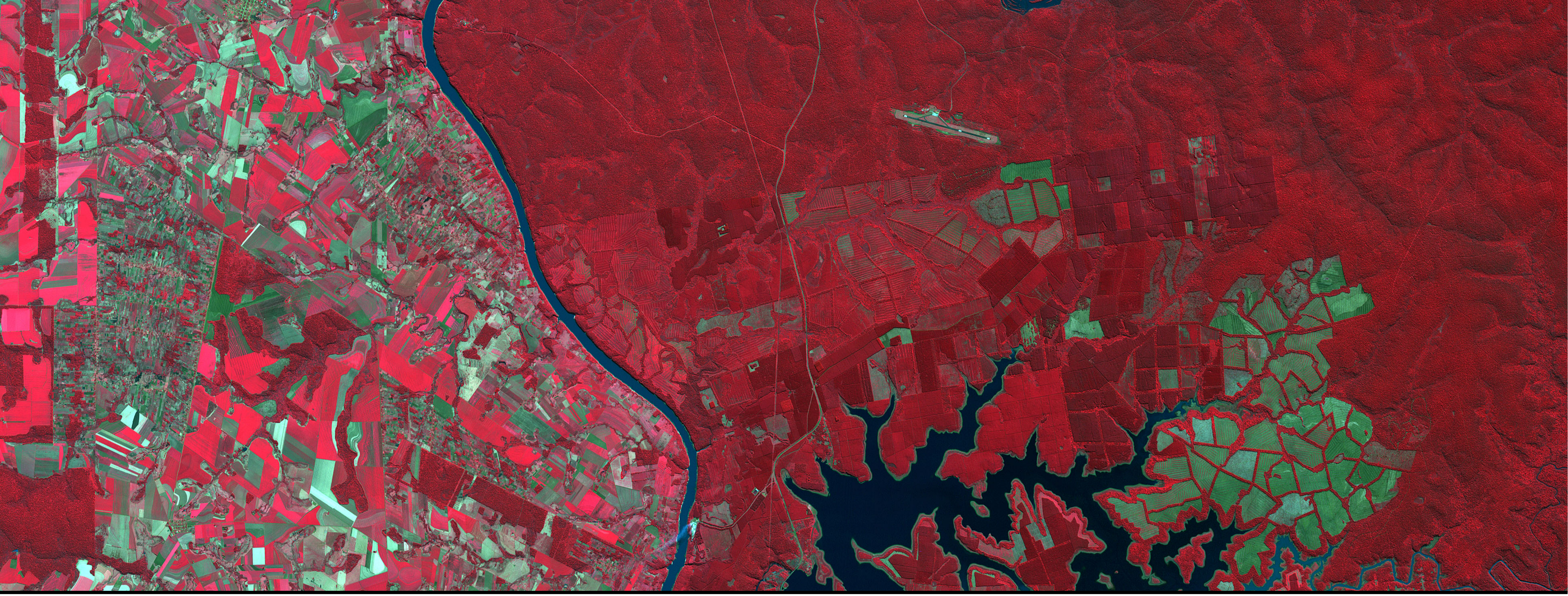
Benefits of Estimating ET from Remote Sensing Data

- Provide relatively frequent and spatially continuous measurement of biophysical variables used in estimating ET at different spatial scales including:
  – radiation
  – land surface temperatures
  – vegetation coverage and density
  – precipitation
  – soil moisture
  – weather and climate variables

Global ET Based on MODIS, Averaged over 2000-2006



Source: University of Montana, Numerical Terradynamic Simulation Group



Methods of Estimating ET Based on Remote Sensing

Remote Sensors and Observations for ET

Satellite	Sensor	Parameter
Terra and Aqua	MODIS	• Normalized Difference Vegetation Index (NDVI) • Leaf Area Index (LAI) • Albedo (fraction of surface solar radiation reflected back)
Landsat	OLI, ETM+, TIRS	• Spectral Reflectance • Thermal Emission

Importance of Landsat for ET

- Allows field-level ET (30 m resolution) – much higher resolution than MODIS-based ET (1 km)
- Has a thermal band that is important for some ET approaches

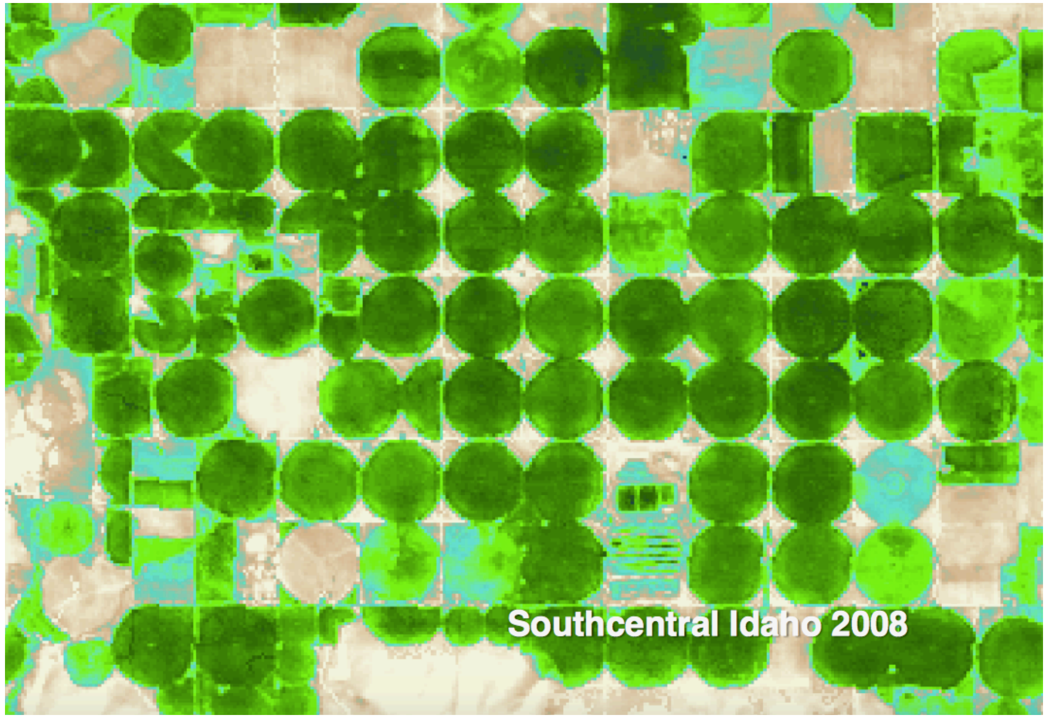


Image Credit: Richard Allen, University of Idaho

Estimation of ET – not easy!

- ET can be derived primarily from:
  - Surface Water Balance
    - ET = Precipitation + Irrigation – Runoff – Ground Water + Vertical Water Transport ± Subsurface Flow ± Soil Water Content
  - Surface Energy Balance
    - ET (Latent Heat Flux) = Net Surface Radiation – Ground Heat Flux – Sensible Heating Flux
  - Meteorological and Vegetation/Crop Data (Penman-Monteith Equation)

Reference: http://www.fao.org/docrep/X0490E/x0490e04.htm#determining%20evapotranspiration

ET Estimation by Land Surface Models

Integrate satellite and ground observations within sophisticated numerical models based on water and energy balance methods

Remote Sensing Inputs

- Surface Solar Radiation
  - from atmospheric models with satellite data assimilation
- Precipitation (TRMM and Multi-Satellites)
- Vegetation Classification & Leaf Area Index (MODIS & AVHRR)
- Topography (Landsat)

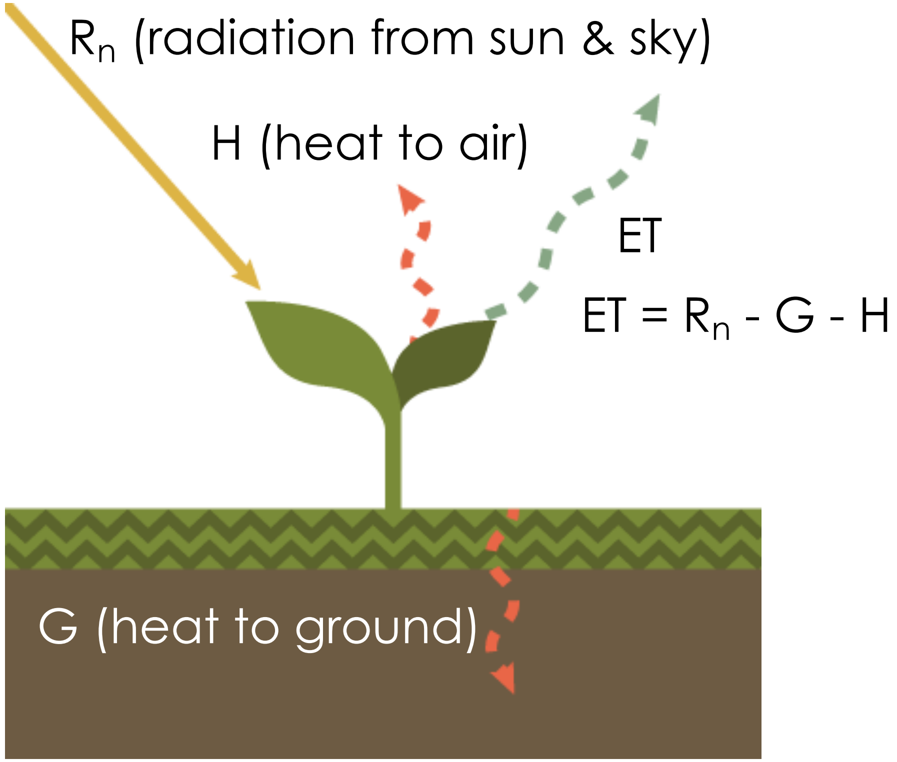
Integrated Outputs

- Soil Moisture
- Evapotranspiration
  - Surface/Sub-Surface Runoff
  - Snow/Water Equivalent

Global Land Data Assimilation System (GLDAS): http://ldas.gsfc.nasa.gov

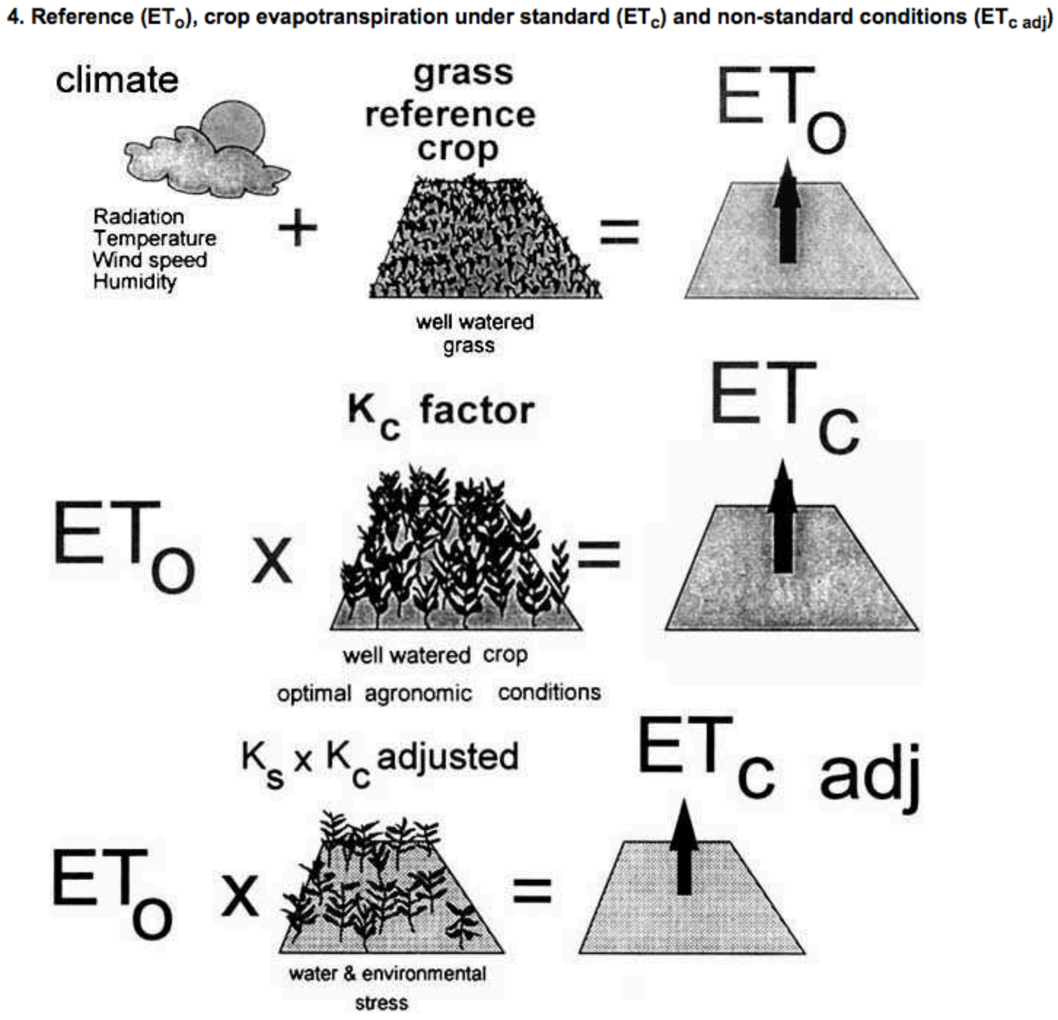
ET Estimation by Surface Energy Balance

- Used by multiple groups to develop ET products
- Uses MODIS & Landsat
  - land surface temperatures
  - land cover
- Calculated by a "residual" of the energy balance – driven by **thermal energy**



Based on imagery from Rick Allen, *Additional ET Observation Platforms: Towards an Integrated Observation Capability*

ET Estimation from Vegetation and Crop Information



- ET_o: reference ET for well-watered grass reference (Penman-Moneith Equation)
- ET_c: crop ET for standard crop conditions:
  - disease free, well fertilized, grown in large fields, optimum soil water conditions, achieving full production under given climatic conditions
- $ET_{c\ adj}$: adjusted for non-standard crop conditions
- K_c: crop coefficient

Image Credit: http://www.fao.org/docrep/X0490E/x0490e04.htm#determining%20evapotranspiration

Penman-Monteith Equation for ET_o

$$\lambda ET = [\Delta(R_n\text{-}G)+\rho_a\, C_p(e_s - e_a)/r_a]/[\Delta+Y(1+r_s/r_a)]$$

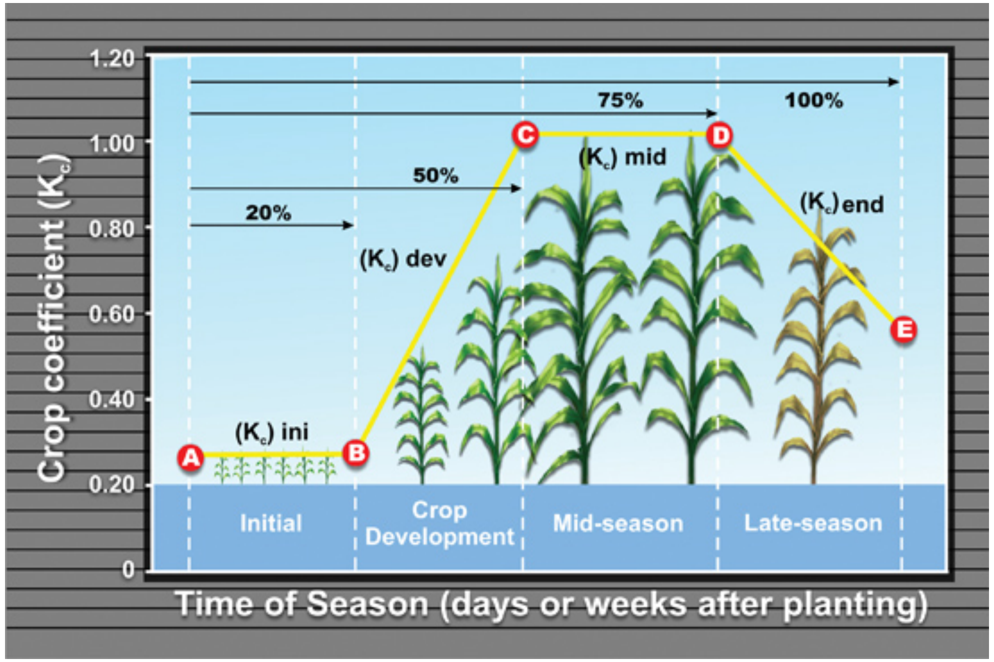
- Δ: slipe of saturation vapor pressure
- R_n: net surface radiation
- G: ground heat flux
- $(e_s\text{-}e_a)$: vapor pressure deficit
- r_a & r_s: aerodynamic & surface resistance
- γ: psychrometric constant
- λ: latent heat constant
- c_p: specific heat constant
- ρ_a: Air density

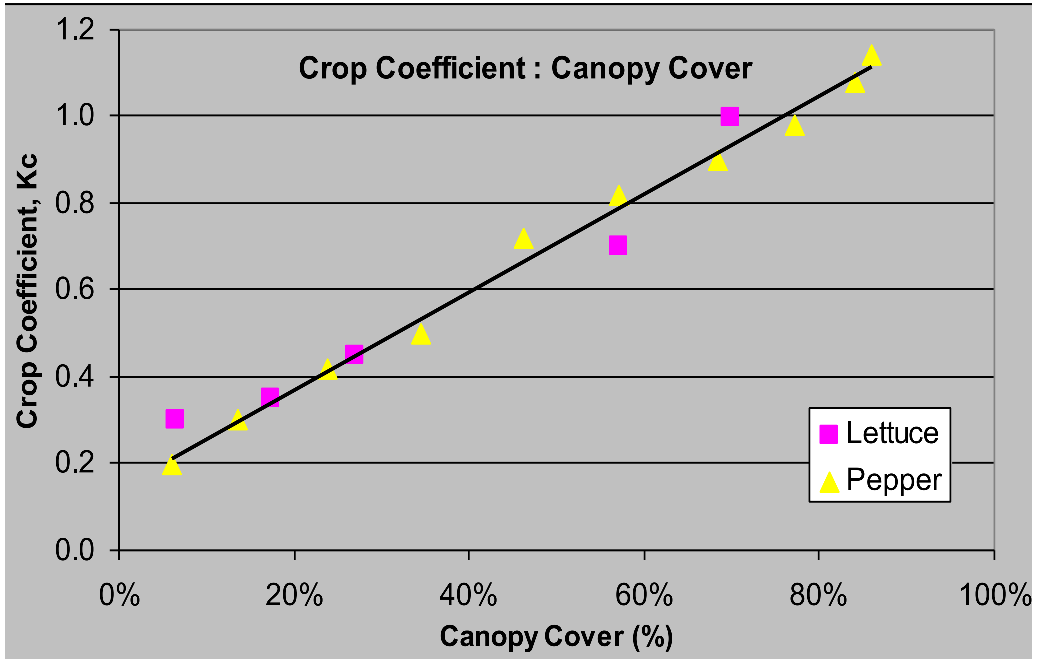
- Requires climate and crop information
- r_a & r_s depend on Vegetation Height, Leaf Area Index (LAI)
- R_n depends on the fractional solar radiation reflected back from the surface (albedo)
- LAI and albedo are both available from MODIS

Reference: http://www.fao.org/docrep/X0490E/x0490e06.htm#penman%20monteith%20equation

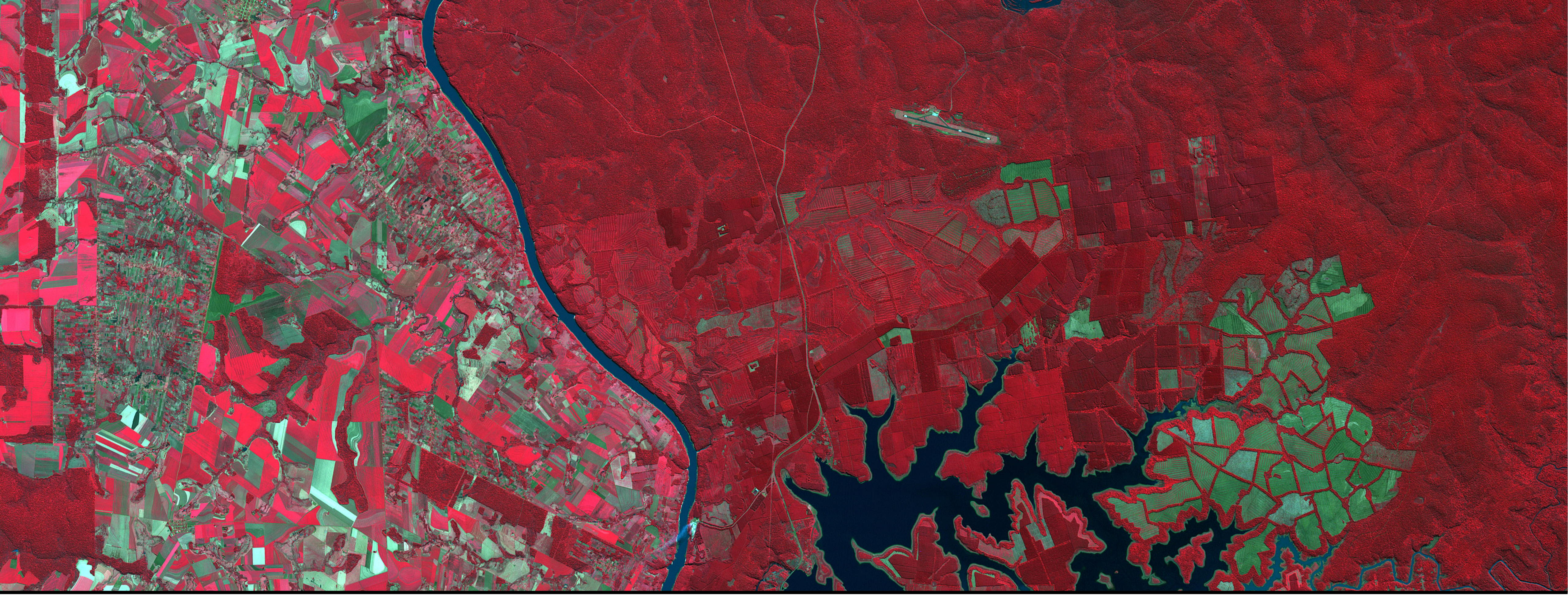
Crop Coefficient (K_c) and Normalized Vegetation Index (NDVI)

- K_C is related to light interception (ground cover)
- There is a direct relationship between K_C and NDVI
  – available from MODIS





* Image Credits: Tom Trout, USDA



ET Data Products Based on Remote Sensing

ET Data Products Based on Remote Sensing Observations

Global Products

- METRIC: Mapping and EvapoTranspiration at high-Resolution with Internalized Calibration
  – https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf
  – https://c3.nasa.gov/water/static/media/other/Day1_S2-5_Kilic.pdf
  – https://c3.nasa.gov/water/static/media/other/Day1_S3-3_Allen.pdf
- ALEXI: Atmosphere-Land Exchange Inverse Model
  – https://c3.nasa.gov/water/static/media/other/Day1_S1-4_Anderson.pdf
  – http://www.ospo.noaa.gov/Products/land/getd/index.html
- GLDAS: Global Land Data Assimilation System
  – http://ldas.gsfc.nasa.gov/gldas/

ET Data Products Based on Remote Sensing Observations

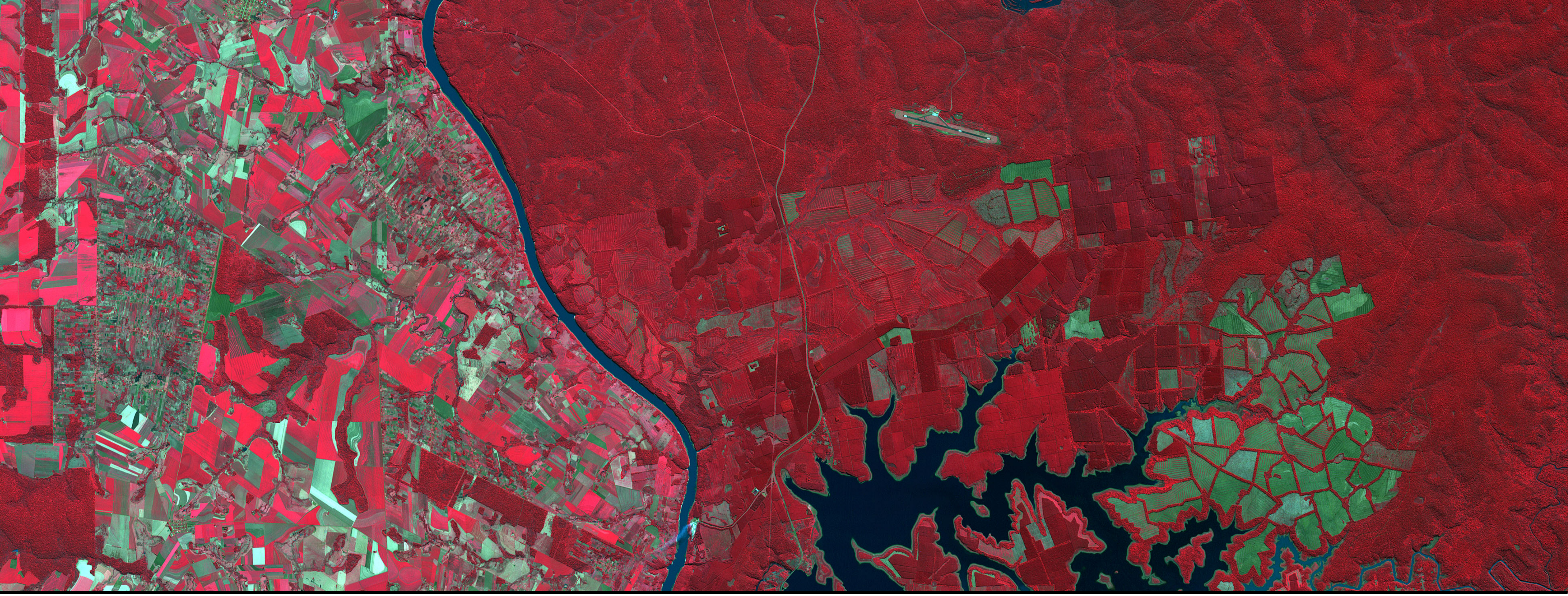
Regional Products (can be adapted for other regions)

- SIMS: Satellite Irrigation Management Support (California)
  - https://c3.nasa.gov/water/static/media/other/Day1_S2-2_Melton.pdf
- NLDAS: North American Land Data Assimilation System (North America)
  - http://ldas.gsfc.nasa.gov/nldas
- SSEBop: Operational Simplified Surface Energy Balance (US & Africa)
  - http://www2.usgs.gov/climate_landuse/lcs/projects/wsmartet.asp
- ETWatch: Multi-Satellite Based Energy Balance Model (China)
  - https://c3.nasa.gov/water/static/media/other/Day2_S1-4_Wu_2.pdf

Summary: Publically Available Global ET Products

ET Source	Method	Remote Sensing Observations
GLDAS	• Land Surface Model • Water and Energy Balance	• TRMM & Multi-Satellite Precipitation • MODIS and AVHRR Land Cover • Landsat Topography
METRIC	• Energy Balance	• Landsat
ALEXI	• Energy Balance	• MODIS • Landsat • GOES

ET Source	Spatial/Temporal Resolution	Data Source	Availability
METRIC	• 30 m (Global) • 2011 – March 2016	Google Earth Engine Evapotranspiration Flux (EEFlux)	http://eeflux-level1.appspot.com/

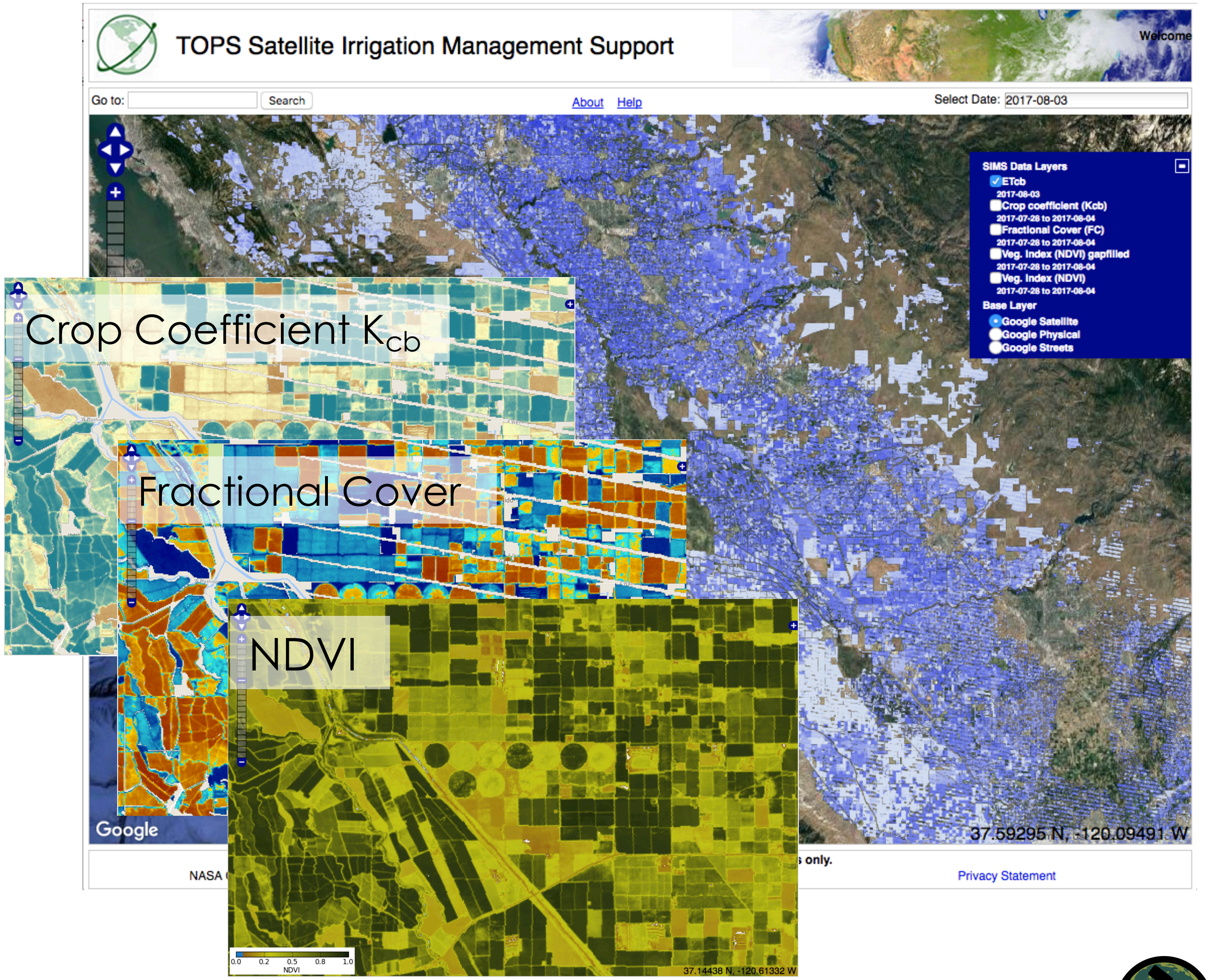


Applications of ET

ET for Irrigation Management

http://ec2-54-196-147-232.compute-1.amazonaws.com/dgw/sims/

- Beta web interface complete
- Web tool publicly accessible
- Being tested by multiple growers
- Integrated with UCCE CropManage irrigation management tool
- Prototype calculator for on-farm water use efficient metrics completed

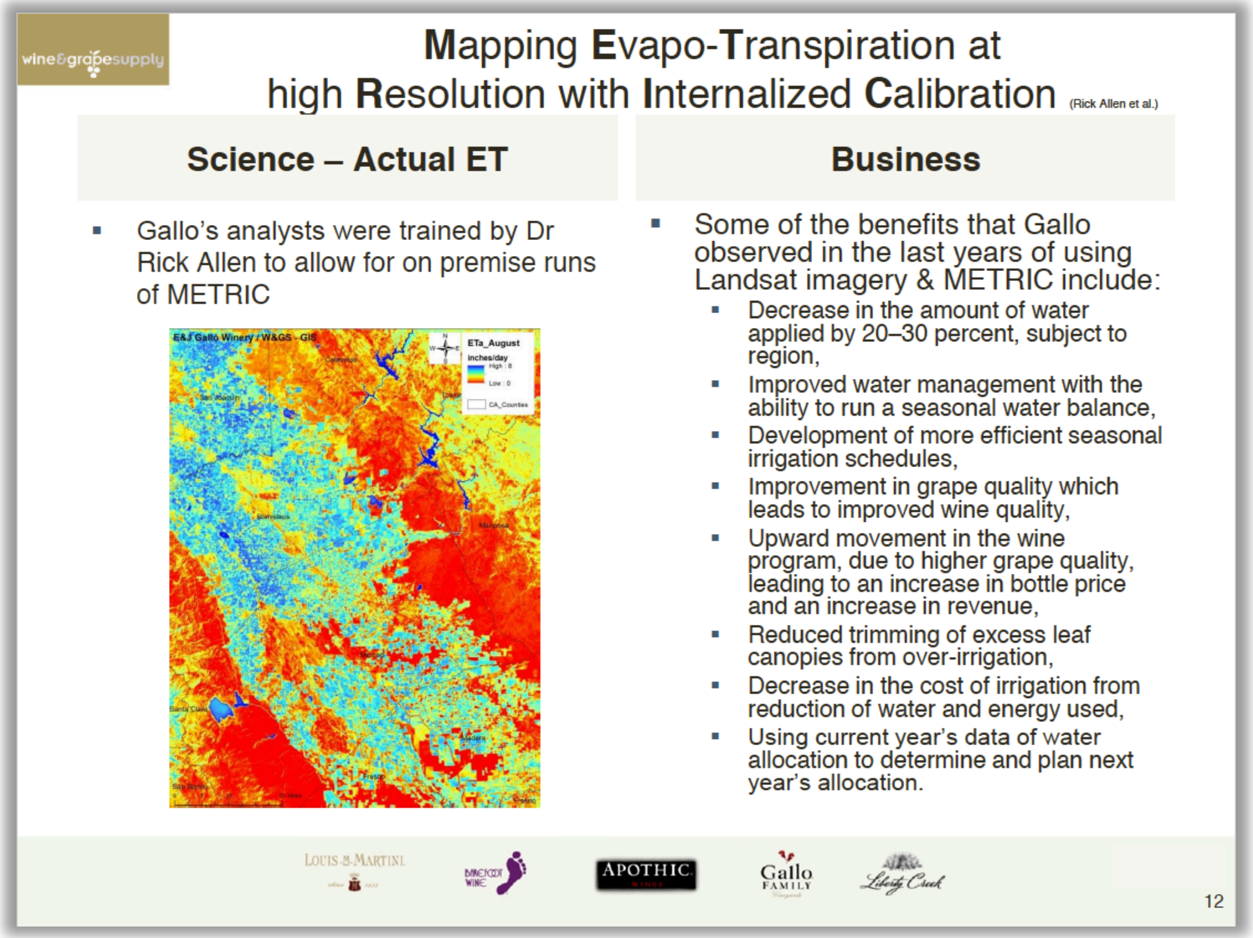


Reference: https://c3.nasa.gov/water/static/media/other/Day1_S2-3_Mendez.pdf

ET for Irrigation Management

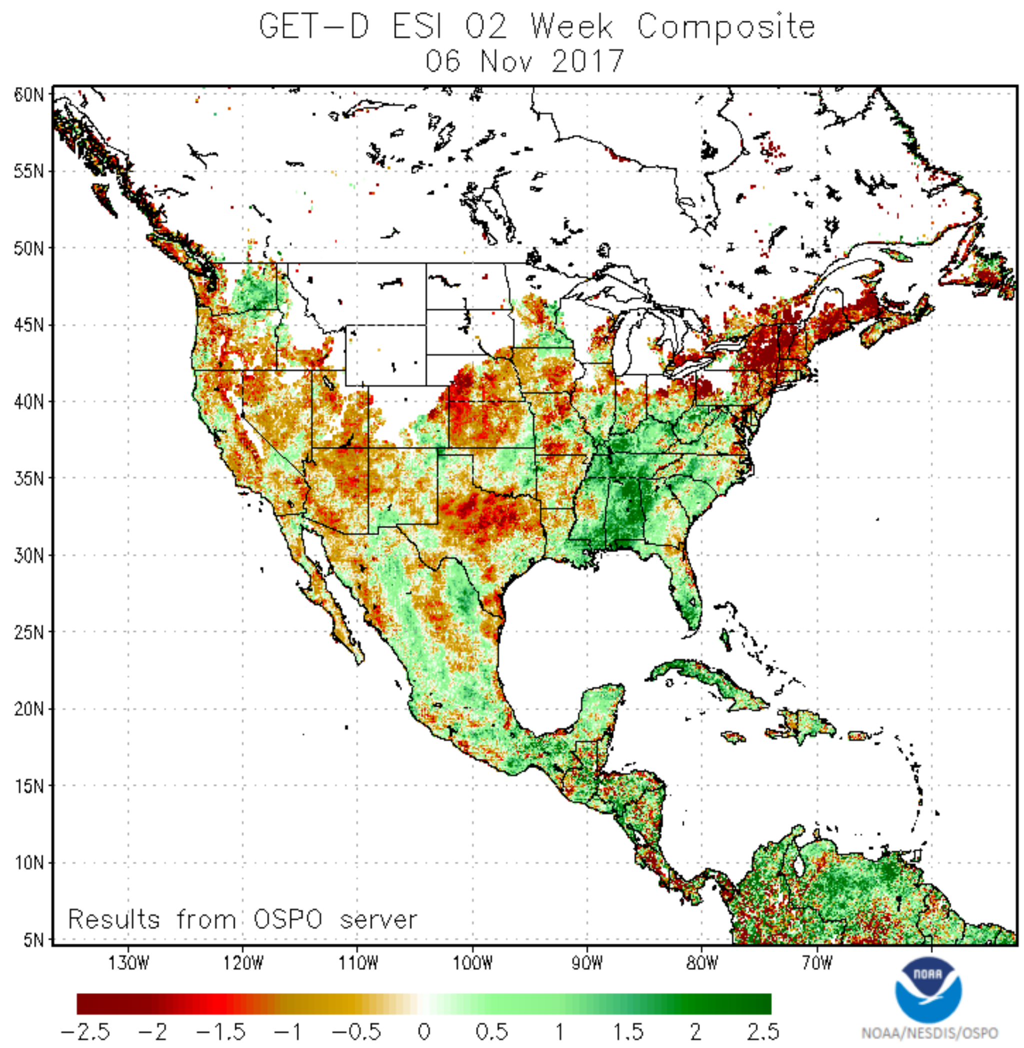
http://ec2-54-196-147-232.compute-1.amazonaws.com/dgw/sims/

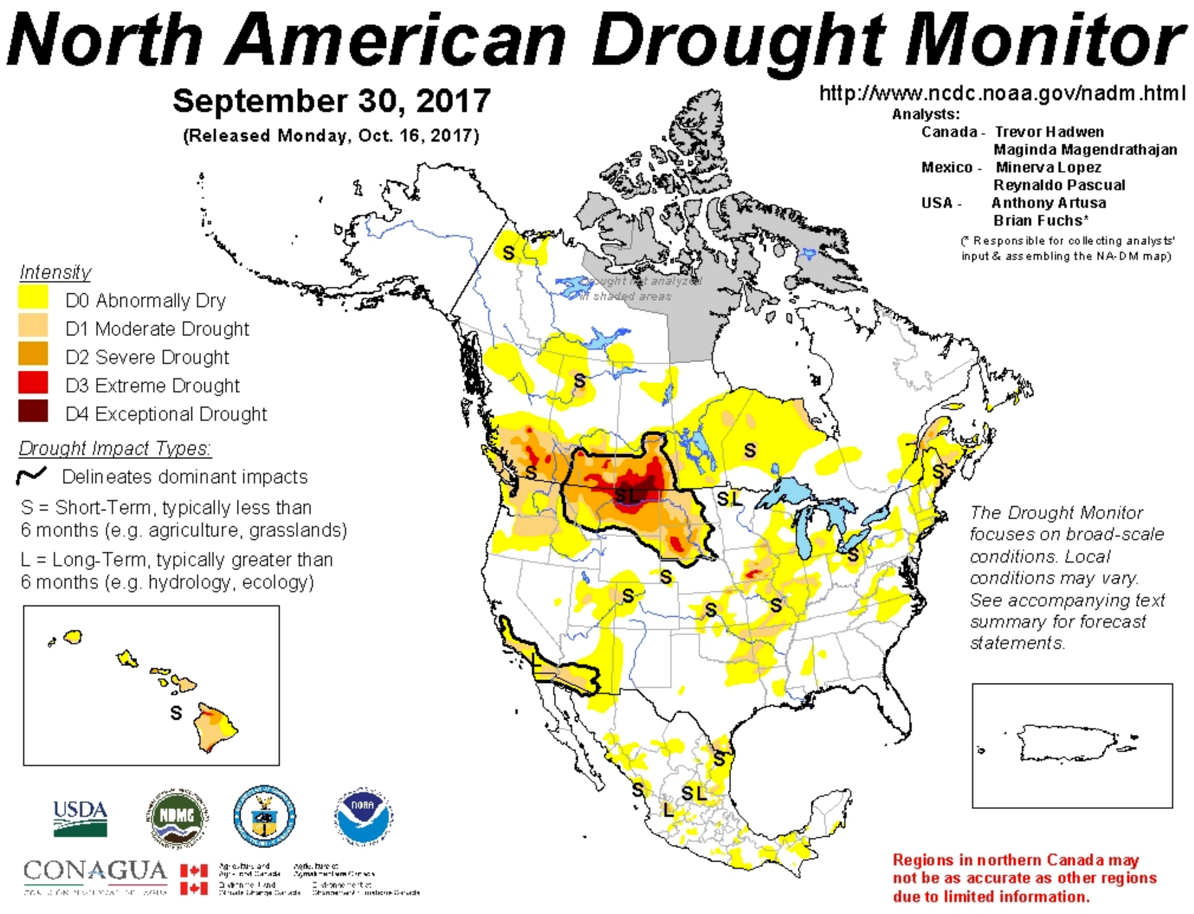
- Landsat-based ET helps wine producers and grape growers in California plan timing and irrigation



Reference: https://c3.nasa.gov/water/static/media/other/Day1_S2-3_Mendez.pdf

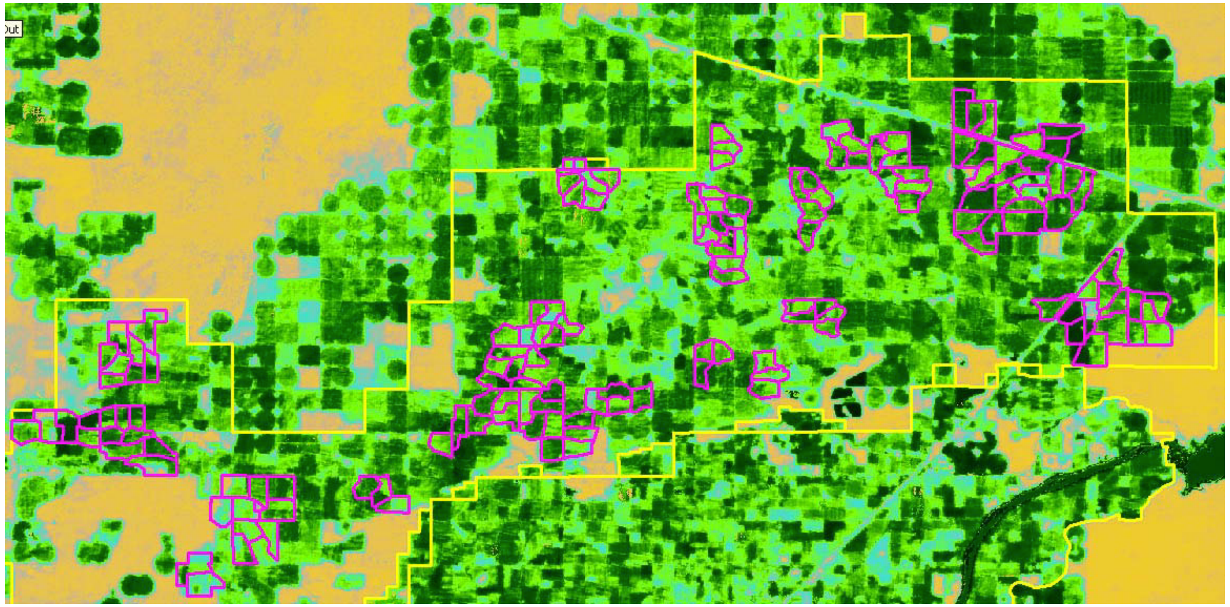
ET for Drought Monitoring Over North America





ET for Water Allocation

- METRIC ET used for deciding water deficit
- Example
  - based on the ET and NDVI analysis, Idaho Department of Water Resources verified that certain fields claimed to be water deficient were not

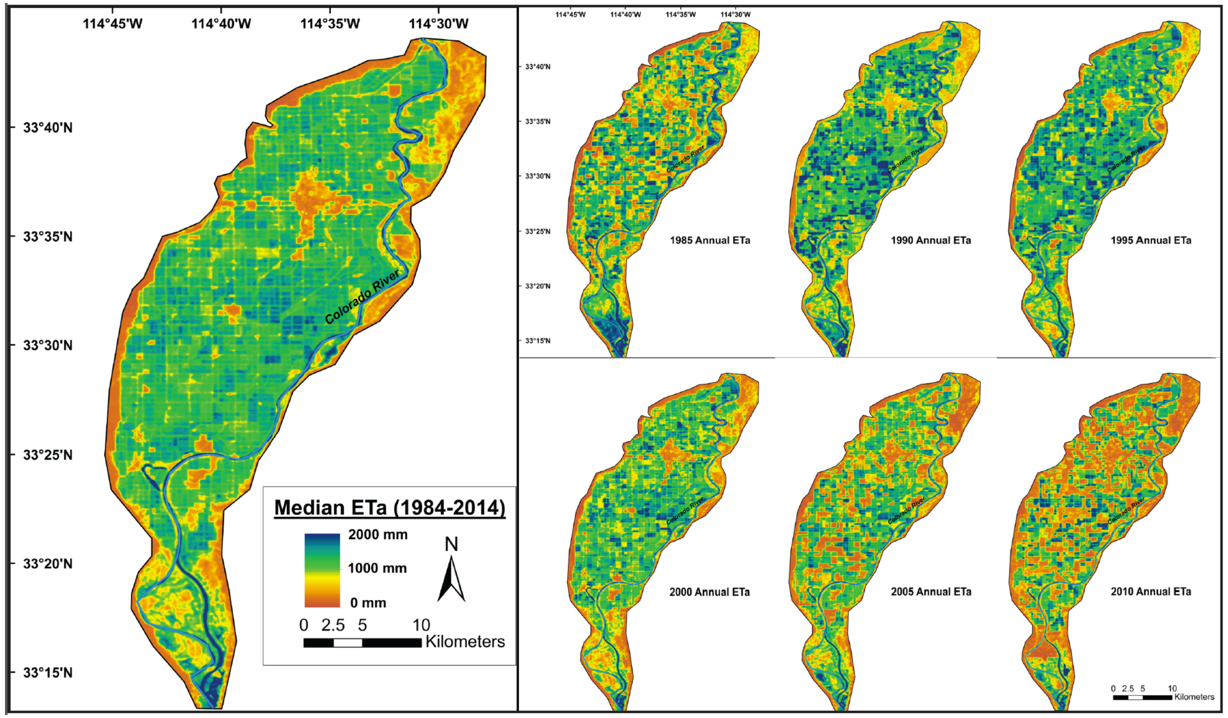


Purple polygons are fields that claimed to be water short in 2006

Reference: https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf

ET for Water Allocation

- The impact of water management decisions were more visible than climate drivers on crop water use (evapotranspiration) changes over time
- The SSEBop ET modeling approach was stable in processing 3,396 Landsat images and generating reliable estimates for trend analysis
- Quantified the association between crop fallowing programs and water savings



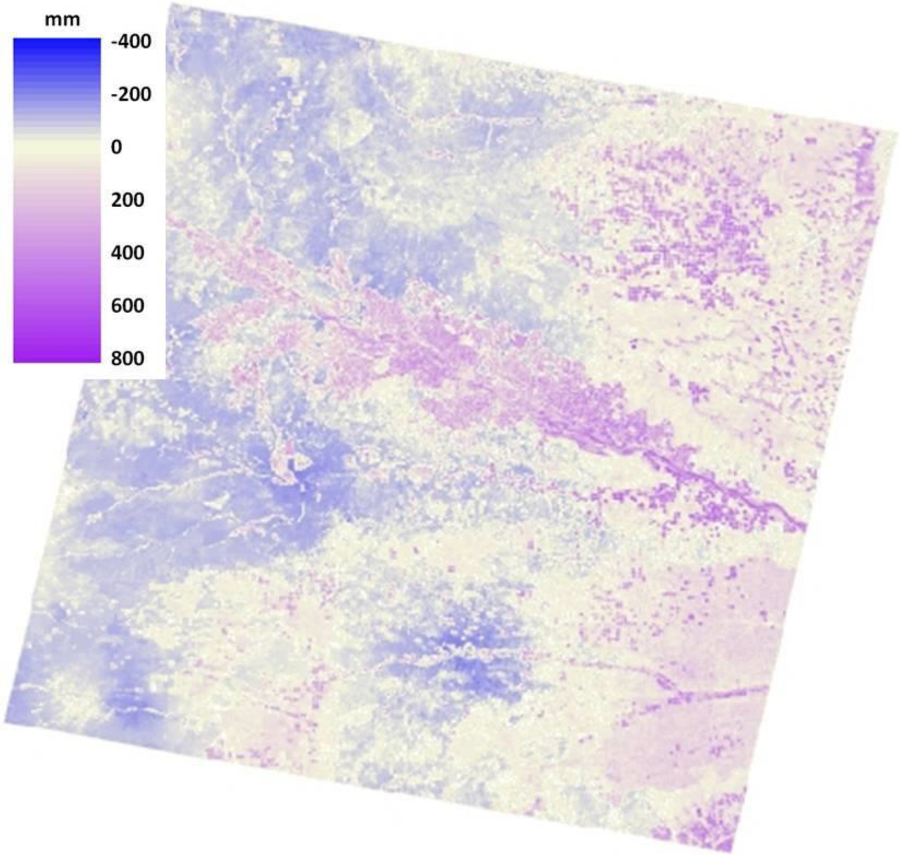
Median annual ET estimates for the Palo Verde Irrigation District (PVID) obtained from the SSEBop model over 1984-2014. Also shown are selected time-series imagery of ET for every 5 years since 1985. Image credit: Senay et al.

Reference: Senay, G., et al. Landsat based historical (1984-2014) crop water use estimates and trends in the Southwestern United States. AGU 2016.
https://landsat.gsfc.nasa.gov/watching-water-use-in-the-southwest/

ET Used in Planning for Aquifer Management

METRIC ET, together with precipitation, helped estimate Ogalalla Aquifer Recharging

Nebraska



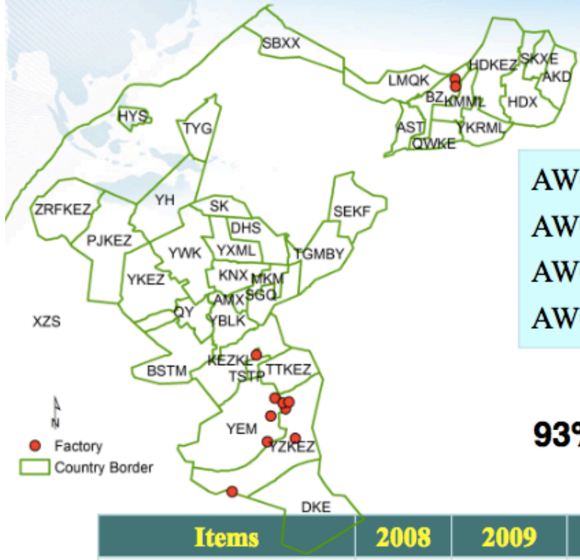
Evapotranspiration minus precipitation for April 1- Oct 31, 1997, Path 33, Row 31

Reference: https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf

ET Used in Agriculture Water Use in China

- Based on ET from ETWATCH and rainfall data excessive use of water for agriculture was noted 2008-2013
- Very useful for planning water resource allocation

Actual Agricultural Water Consumption at Ertanggou



$AWC_{AG} = AWC_{Total} - AWC_{RAIN}$

AWC_{AG} : Water consumption by irrigation

AWC_{Total} : Total water consumption from cropland

AWC_{RAIN} : Water consumption by rainfall

93% more than allowed

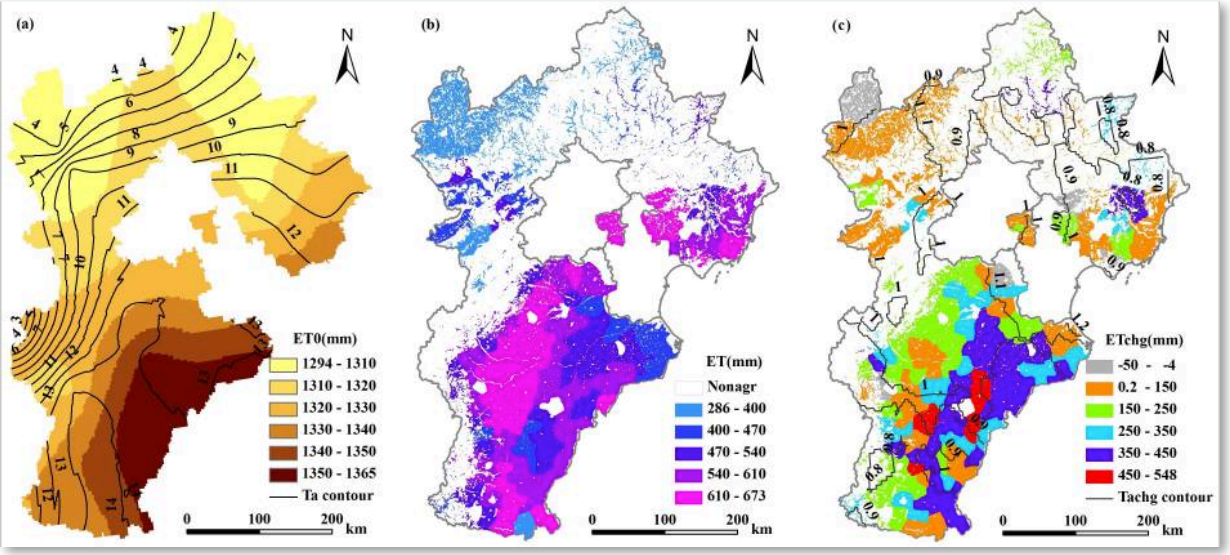
Items	2008	2009	2010	2011	2012	2013	Average
$AWC_{Total}(10^6 m^3)$	166.7	157.6	142.5	165.6	162.7	192.8	164.6
$AWC_{RAIN}(10^6 m^3)$	9.9	3.2	11.9	4.4	6.6	6.3	7.0
$AWC_{AG}(10^6 m^3)$	157	154	131	161.2	156	187	158

RADI www.radi.cas.cn

Reference: https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf

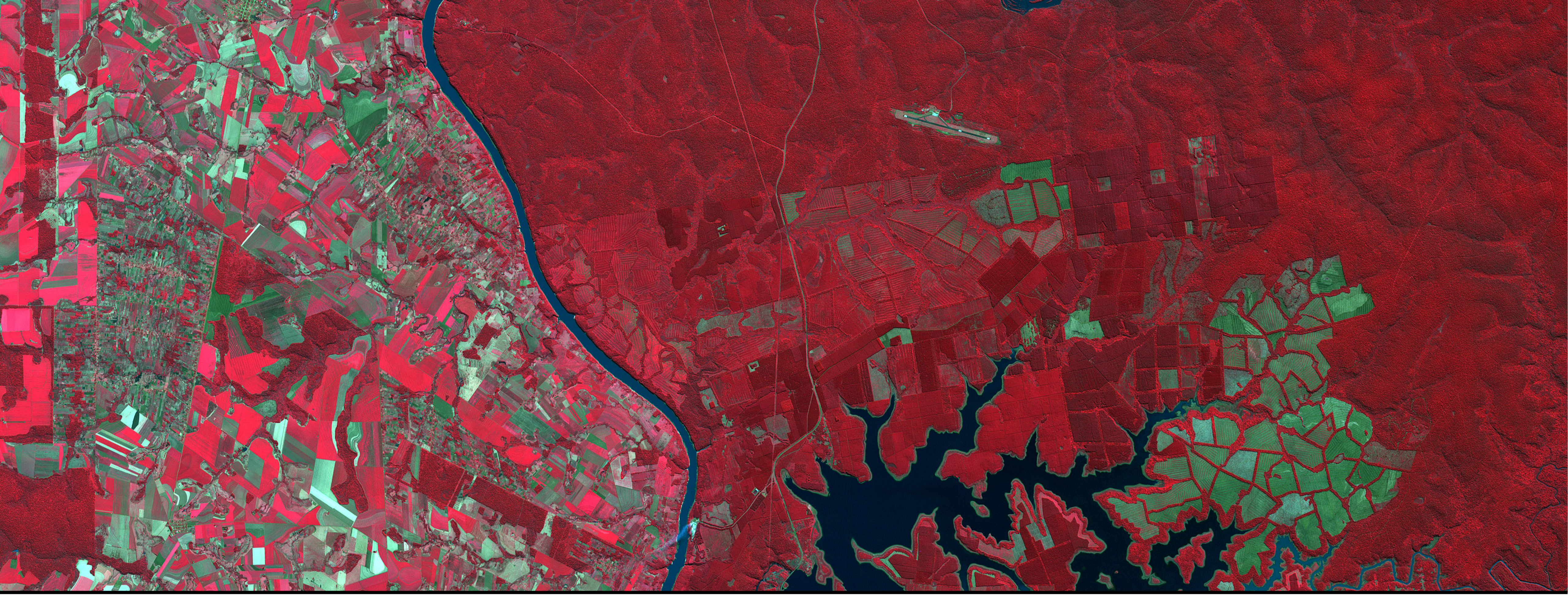
ET Used to Track Agricultural Water Consumption

- Estimated agricultural water consumption (AWC) based on station data (1984-2008) and MODIS ET data
- Found AWC increased significantly in the past 25 years, with the exception of a few counties
- The integration of meteorological and satellite data allows for the estimation of actual ET beyond the record available from satellite data



Distribution of annual mean ET_0 (a), actual ET (b), and changes in averaged ET for the period of 1984–1993 to 1999–2008 (c).

Reference: Yuan, Z., & Shen, Y. (2013). Estimation of Agricultural Water Consumption from Meteorological and Yield Data: A Case Study of Hebei, North China. PLoS ONE, 8(3). doi:10.1371/journal.pone.0058685



METRIC: Mapping EvapoTranspiration at high-Resolution with Internalized Calibration

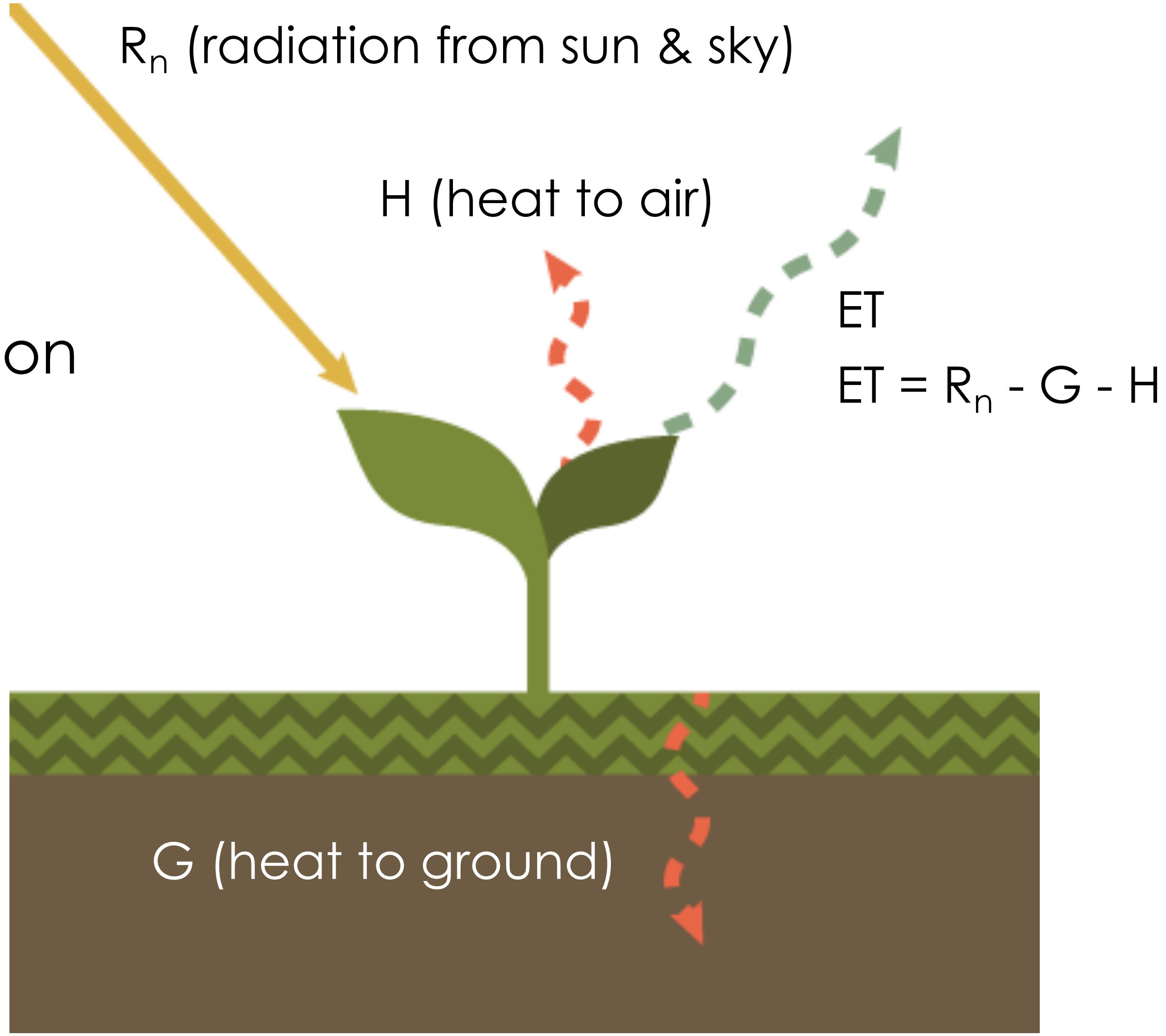
Courtesy of Rick Allen, Univ. Idaho, Member, USGS/NASA Landsat Science Team

METRIC: Based on Energy Balance

- Energy Balance (EB)
  - Remember: ET is the water that changes from liquid to water vapor
  - Liquid to vapor conversion requires energy
  - We “look” for the energy used to produce the evaporation
  - EB components can be derived from the temperature of the surface

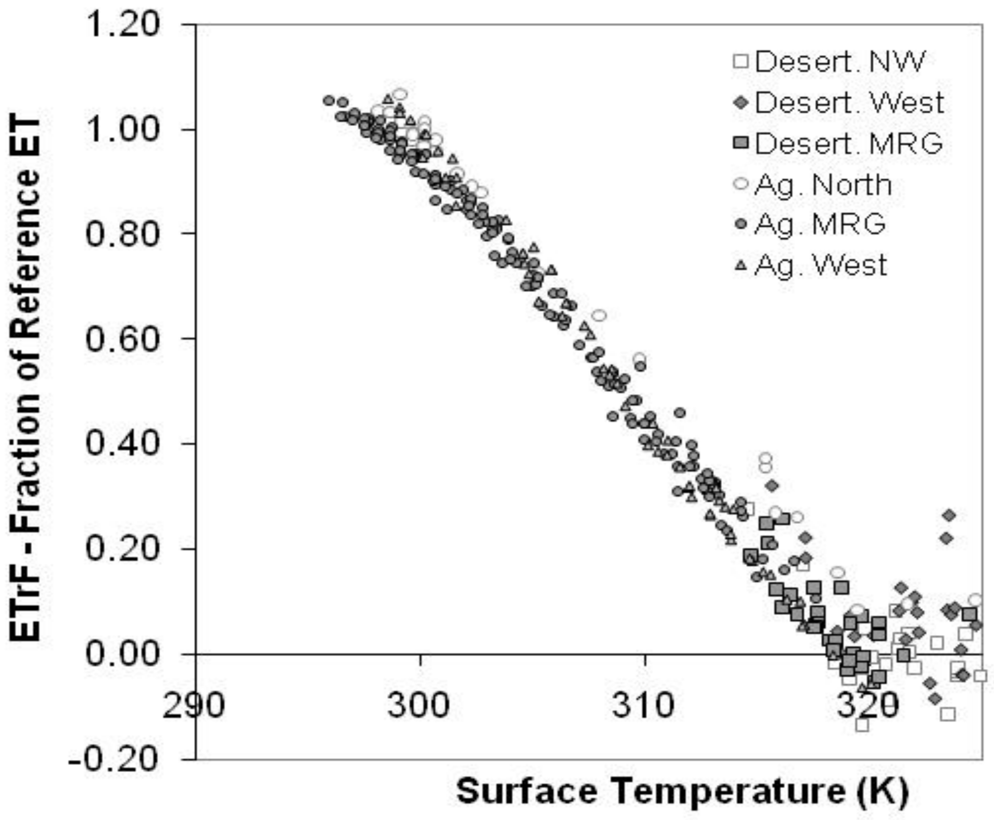
ET is Calculated as a Residual of the Energy Balance

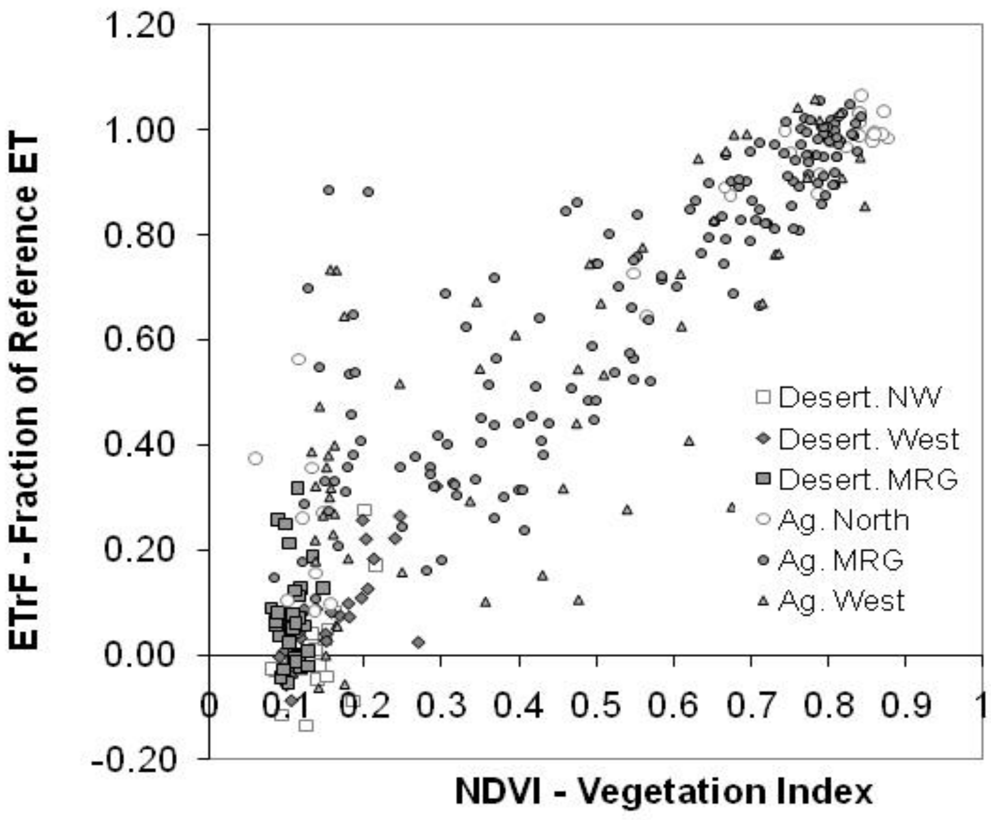
Basic truth: evaporation consumes energy



ET Is Influenced More by Surface Temperature Than Vegetation

Middle Rio Grande, New Mexico





General EB Components in METRIC

METRIC uses Landsat band reflectances and weather information to get the EB components

- Net Radiation (R_n)
  - Reflected shortwave from satellite
  - Incoming shortwave from theory
  - Emitted longwave from satellite
  - Incoming longwave from emitted and atmospheric transmissivity
- Soil Heat Flux (G)
  - Function of H for nearly bare soil and function of Rn for vegetation
- $\lambda E = R_n - G - H$

Reference: Allen, R. G., et al. (2007). Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. Journal of Irrigation and Drainage Engineering, 133(4), 395-406. doi:10.1061/(asce)0733-9437(2007)133:4(395)

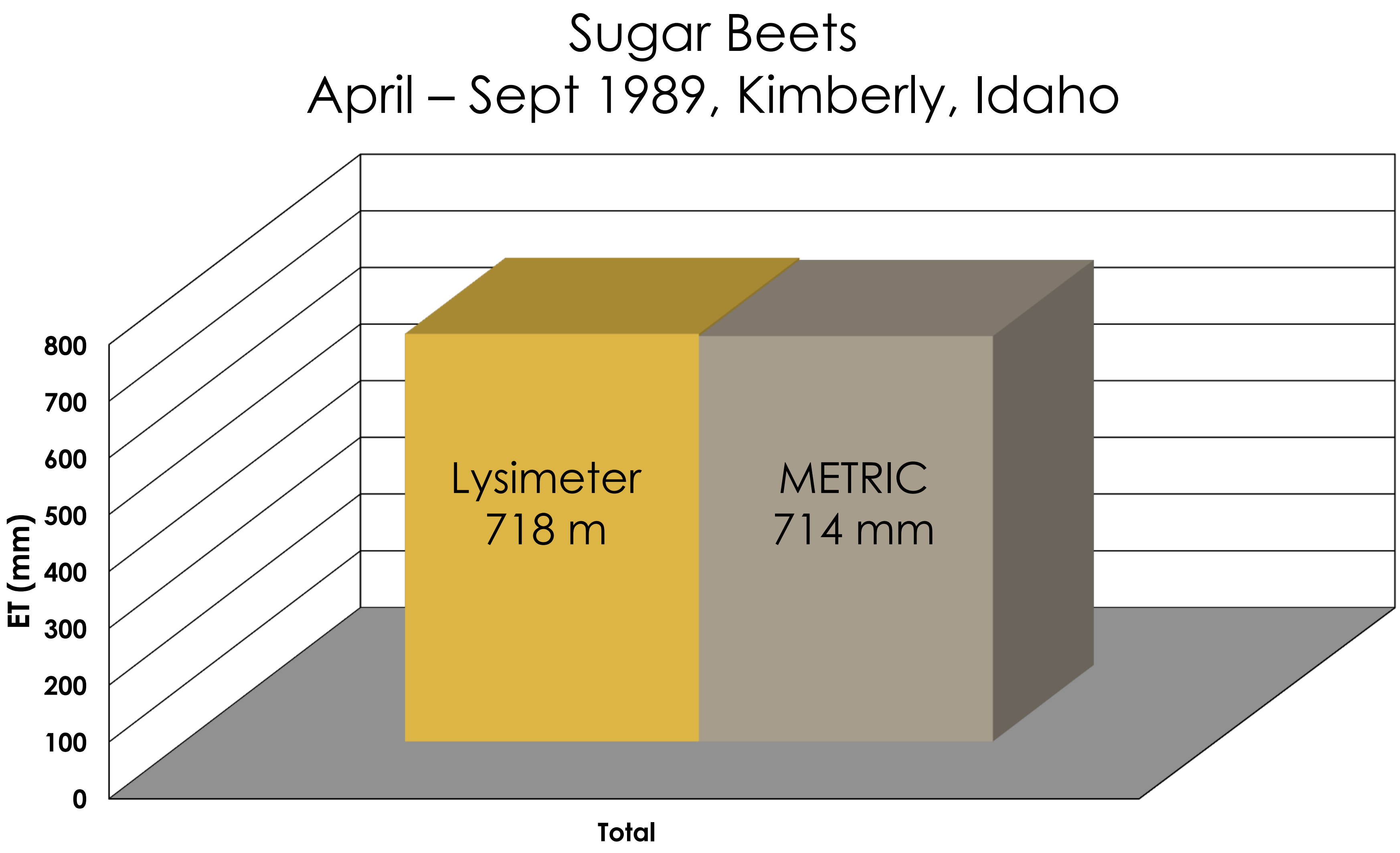
General EB Components in METRIC

METRIC uses Landsat band reflectances and weather information to get the EB components

- Sensible Heat Flux (H)
- Near surface vertical air temperature gradient (dT) keyed from surface temperature (Ts) – calibrated to each image date (dT = a + b Ts)
- Aerodynamic resistance from
  – Wind speed at blending height (from gridded or local weather)
  – Aerodynamic roughness from vegetation indices and land use type
  – Buoyancy effects from iterative solutions

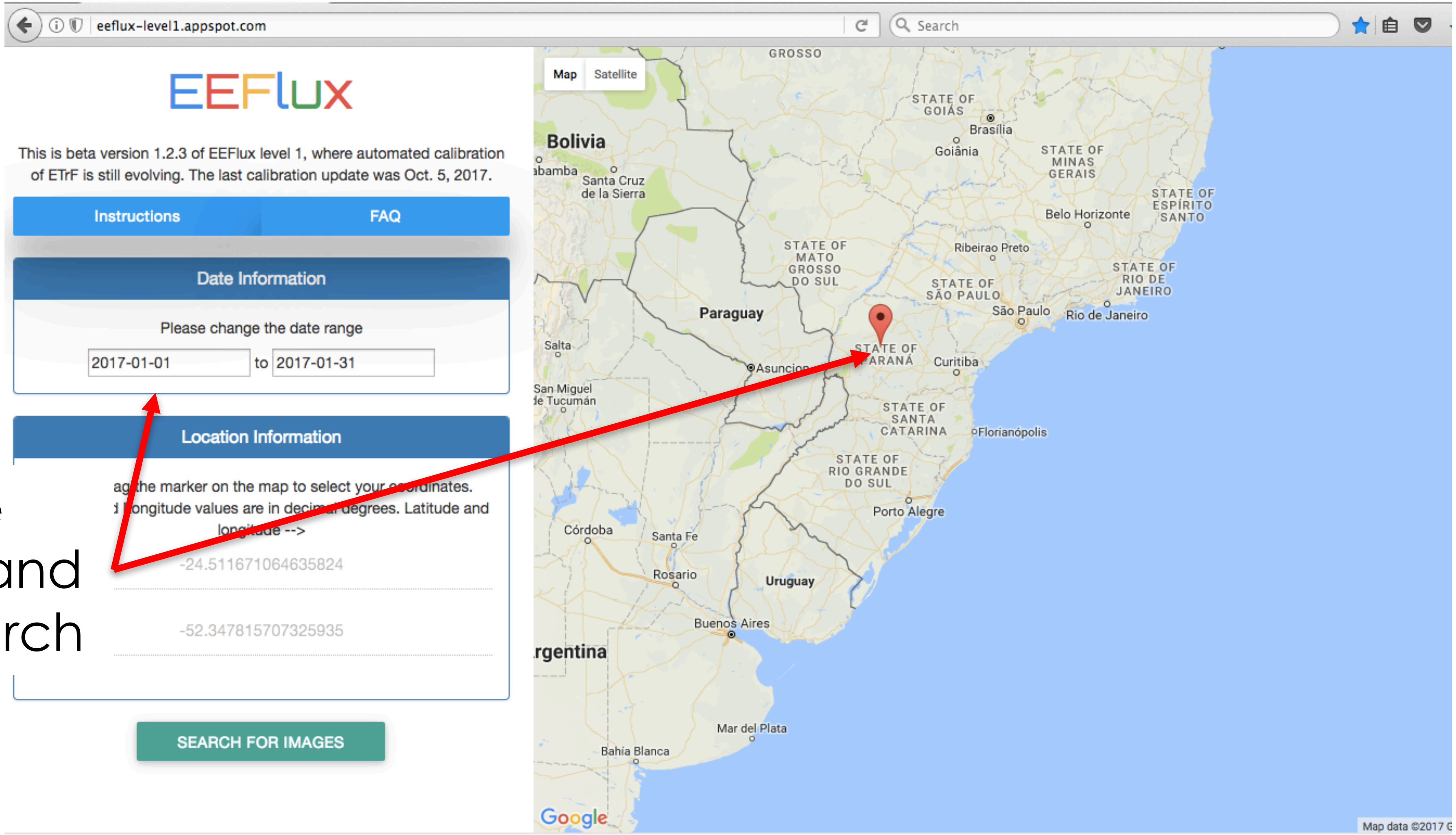
Reference: Allen, R. G., et al. (2007). Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. Journal of Irrigation and Drainage Engineering, 133(4), 395-406. doi:10.1061/(asce)0733-9437(2007)133:4(395)

Comparison of Seasonal ET by METRIC with Lysimeter



EEFlux: METRIC Data Access from Google Earth Engine

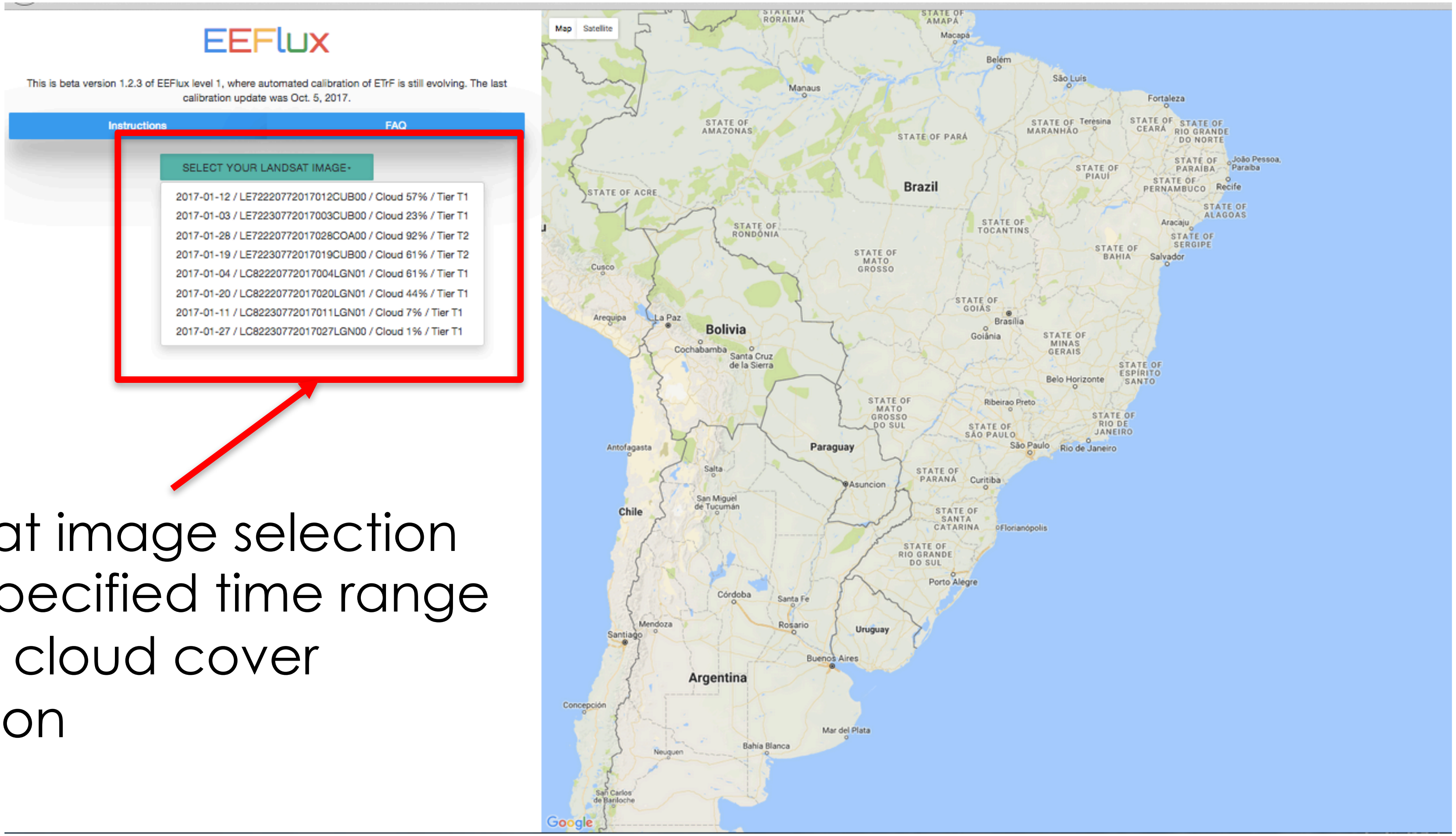
http://eeflux-level1.appspot.com/



Interactive temporal and spatial search

EEFlux: Google Earth Engine Based METRIC ET

http://eeflux-level1.appspot.com/

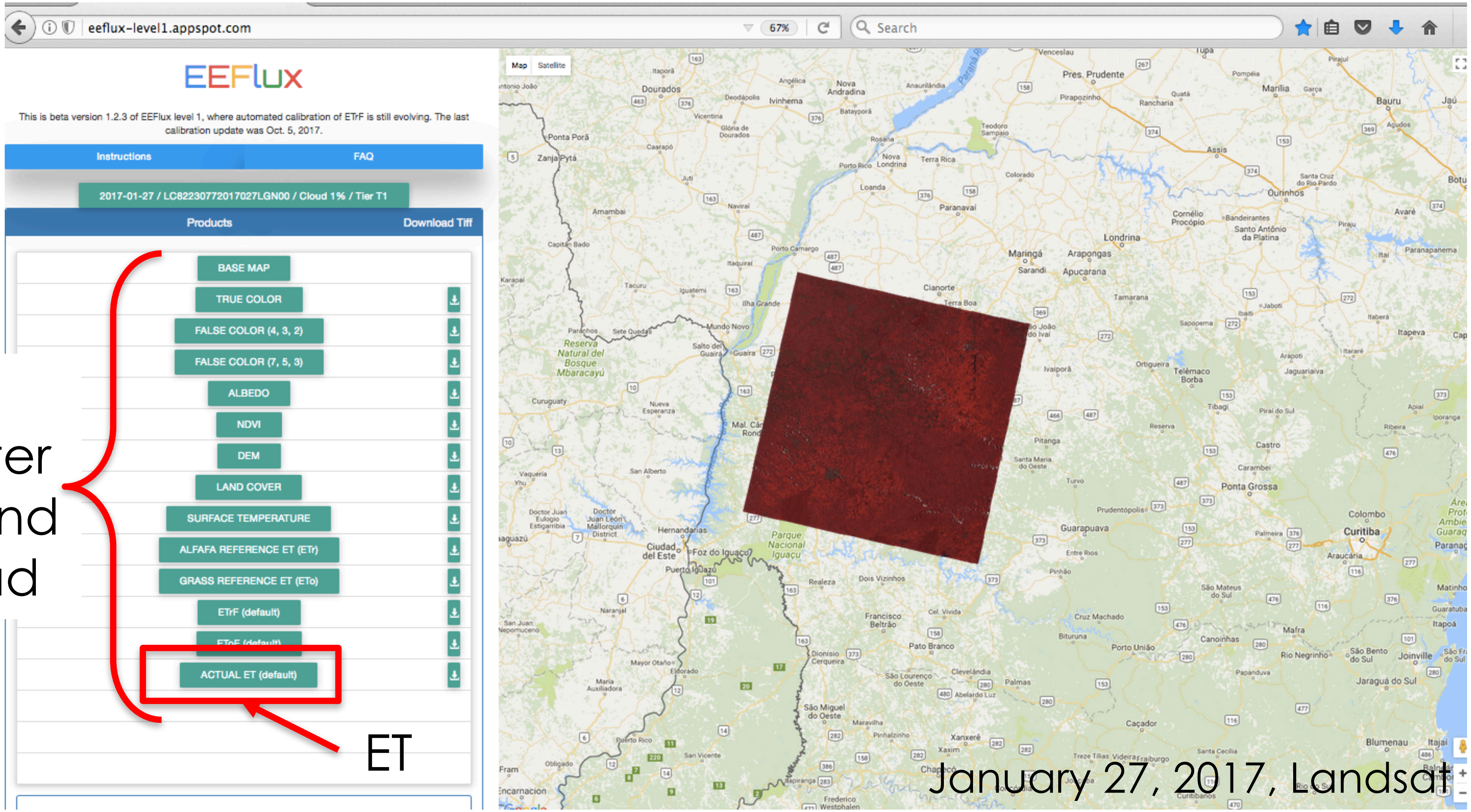


Landsat image selection from specified time range with % cloud cover selection

EEFlux: Google Earth Engine Based METRIC ET

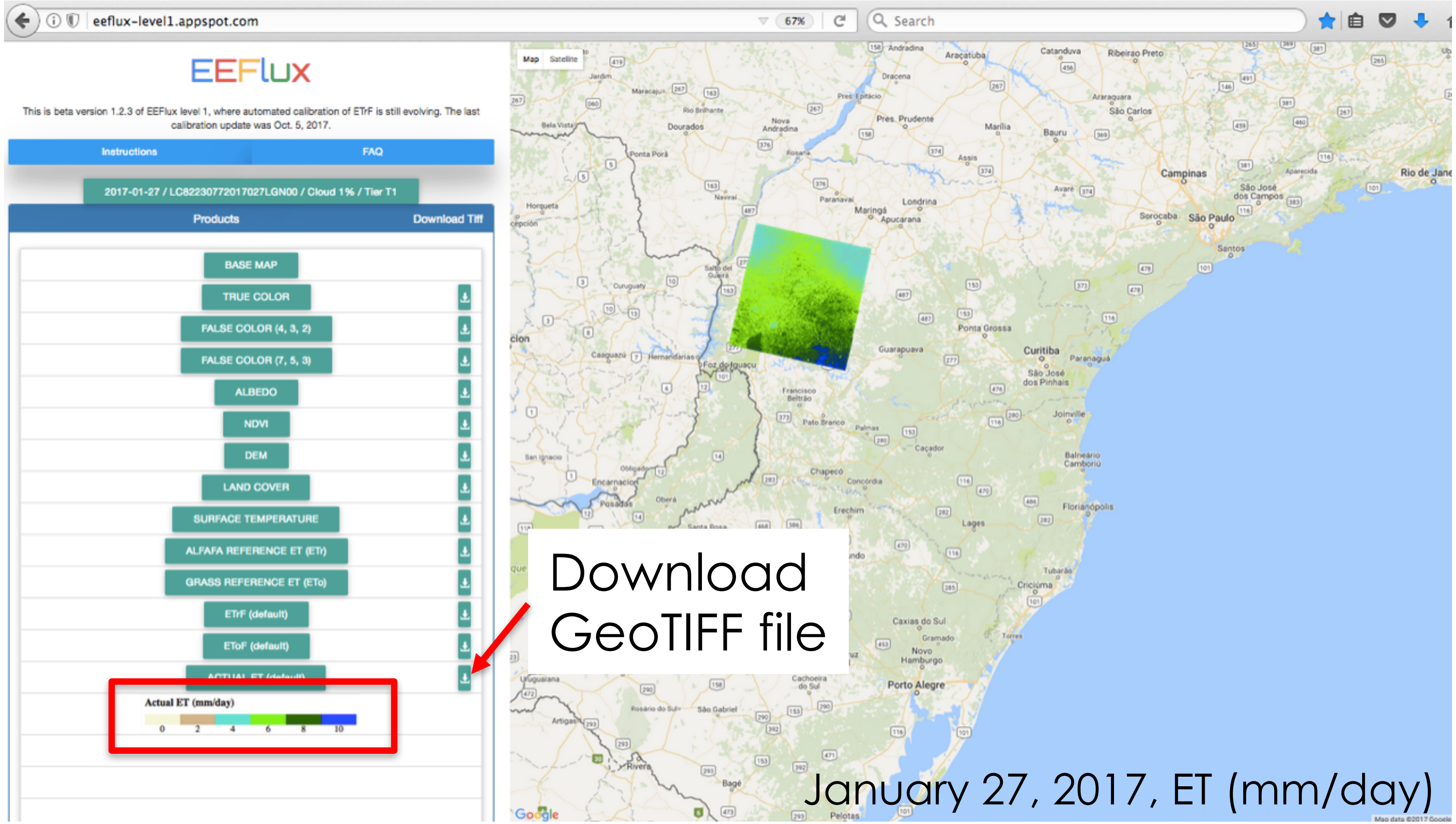
http://eeflux-level1.appspot.com/

Select parameter to plot and download



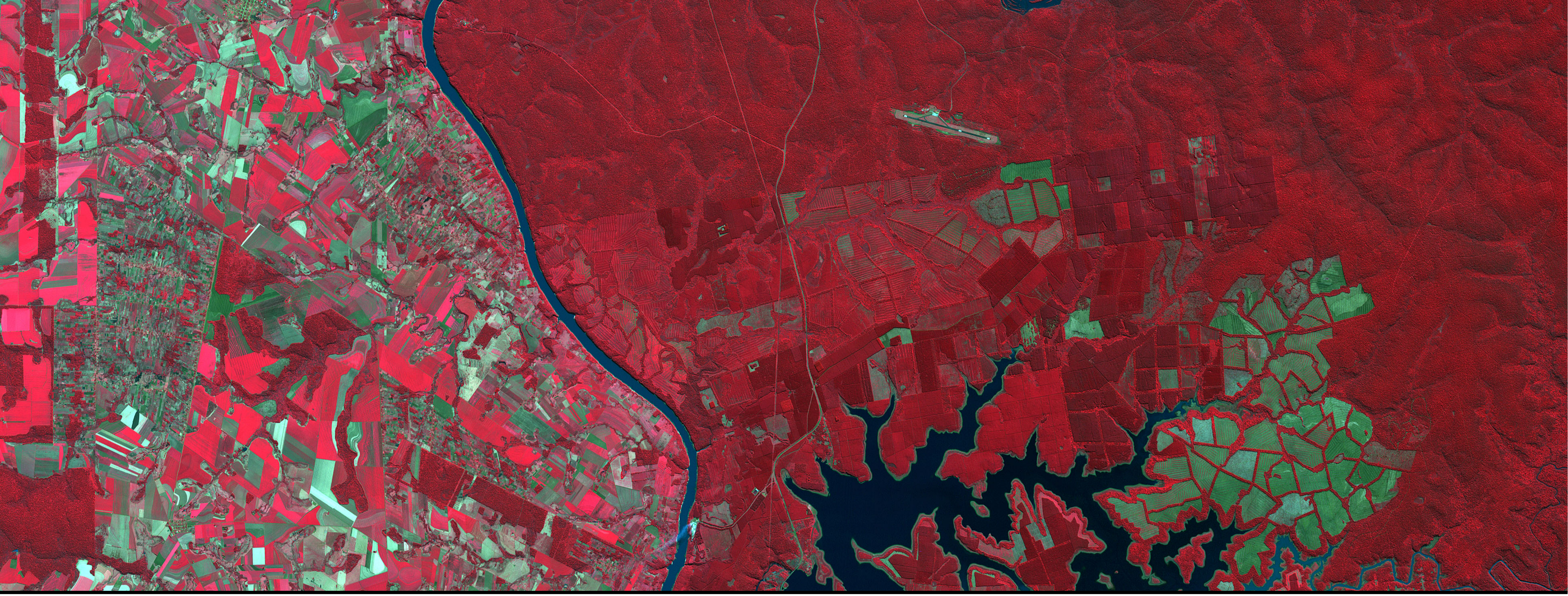
EEFlux: Google Earth Engine Based METRIC ET

http://eeflux-level1.appspot.com/



Summary

- Evapotranspiration is not measured, but calculated by water and/or energy balance methods
- Requires complex algorithm and a variety of climate and land surface data
- Multiple algorithms for estimating ET are available – validation and inter-comparison for regional use are recommended
- Remote sensing data from Landsat and MODIS (land surface temperature, land cover, vegetation index, leaf area index, albedo) are very useful in estimating ET
- For more details see ARSET Webinar on ET:
  – https://arset.gsfc.nasa.gov/water/webinars/apps-et-smap



Next

Hands-on Exercise: ET Data Download for Sau Francisco Watershed